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A techno-economic analysis of using mobile distributed pyrolysis facilities to deliver a forest residue resource

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HIGHLIGHTS

- A model of harvesting forest residues using mobile pyrolysis facilities is created.
- Delivered feedstock costs are examined against conventional woodchip delivery.
- Transport requirements are reduced when using mobile facilities.
- Delivering torrefied wood is the lowest cost pathway when using mobile facilities.
- Using mobile facilities can be cost competitive with woodchip delivery.

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ABSTRACT

Distributed mobile conversion facilities using either fast pyrolysis or torrefaction processes can be used to convert forest residues to more energy dense substances (bio-oil, bio-slurry or torrefied wood) that can be transported as feedstock for bio-fuel facilities. Results show that the levelised delivered cost of a forest residue resource using mobile facility networks can be lower than using conventional woodchip delivery methods under appropriate conditions. Torrefied wood is the lowest cost pathway of delivering a forest residue resource when using mobile facilities. Cost savings occur against woodchip delivery for annual forest residue harvests above 2.5 million m^3 or when transport distances greater than 300 km are required. Important parameters that influence levelised delivered costs are transport distances (forest residue spatial density), haul cost factors, and initial moisture content of forest residues. Relocating mobile facilities can be optimised for lowest cost delivery as transport distances of raw biomass are reduced.

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1. Introduction

Climate change concerns and government policies aimed at reducing greenhouse gas emissions from fossil fuels continue to contribute to an increasing demand for fuels from biomass sources. Forestry residues are an underused biomass resource that have considerable potential for increased utilisation – at present, most are burned on-site at the end of commercial forestry operations. However, like many biomass feedstocks, forest residues suffer from low spatial and energy densities. Typically, forest residues are spread-out over wide areas of land, thus large distances are travelled for collection and delivery to bio-fuel production facilities. If forest residues are transported in their raw form or as woodchips, truck capacity is limited by volume rather than weight and, as a result, more delivery trips are required than if the truck were transporting a more energy dense substance at full weight capacity (Sultana and Kumar, 2011). The combination of low spatial and energy densities of biomass results in high transport costs which, in turn, elevate the final bio-fuel production cost.

One proposed method to reduce the cost of delivering a biomass resource is to implement a network of distributed biomass conversion facilities near the location of forest residues (Badger and Fransham, 2006). These conversion facilities convert raw biomass to a more energy dense substance, which is then transported longer distances to a centralised bio-fuel production facility. Mobile facilities are of particular interest as forest residues are not consistently available at the same location for long periods of time. Mobile distributed conversion facilities ('mobile facilities') can be moved from a depleted region and relocated to a region with abundant forest residues. Relocating mobile facilities reduces transport distances of raw biomass material.

Two processes that are suited for mobile facilities are fast pyrolysis and torrefaction. These are both forms of pyrolysis, which is the thermal decomposition of materials in the absence of oxygen.

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Fast pyrolysis involves high heating rates and short reaction times producing primarily a liquid bio-oil product (Bridgwater, 2012). Torrefaction occurs at lower temperatures than fast pyrolysis and the principal product is a solid char-like substance known as torrefied wood (Acharya et al., 2012). The energy and mass densities of the liquid and solid products are typically higher than that of forest residues or woodchips.

Fast pyrolysis has been the focus of many recent studies (e.g. Oasmaa et al., 2010; Bridgwater, 2012), including techno-economic analyses (e.g. Bridgwater et al., 2002; Wu et al., 2010; Rogers and Brammer, 2012). However, most studies focus on permanent distributed fast pyrolysis facilities and few have considered mobile distributed fast pyrolysis facilities. Research addressing torrefaction technology and its economic advantage for biomass applications is garnering attention (e.g. Uslu et al., 2008; Chew and Doshi, 2011; Phanphanich and Mani, 2011; Acharya et al., 2012), although no literature has been identified that focuses on mobile distributed torrefaction facilities.

This paper investigates the technical and economic impact of using mobile facilities to deliver a forest residue resource to a bio-fuel facility. A model is created to simulate four pathways (Fig. 1a) of delivering a forest residue resource to a bio-fuel facility gate: (i) woodchips (ii) bio-oil (iii) bio-slurry (i.e. a mixture of bio-oil and bio-char) and (iv) torrefied wood. Furthermore, the model includes two point-of-delivery scenarios (Fig. 1b) to account for situations when the bio-fuel facility is either located within or at a distance from the forested region. The model is described in detail in Section 2.

Both fast pyrolysis and torrefaction are well suited for mobile applications. It is possible for each process to be sustained using its reaction products to meet thermal and energy requirements of the system. Therefore, the reaction can continue independently and does not require an electrical grid connection. At present there are no commercial mobile facilities available for either process, although designs for such systems have been made and several pilot projects are in operation (Preto, 2005; Renewable Fuel Technologies, 2011).

Fast pyrolysis and torrefaction are described in Sections 1.1 and 1.2, respectively. The current status of each process and the specifications for the mobile facilities used in this study are also provided.

1.1. Fast pyrolysis

Pyrolysis is the thermal decomposition of materials in the absence of oxygen (Mohan et al., 2006). The products of pyrolysis reactions comprise solid char, liquid bio-oil and syngas, which is a mixture of H_2, CO, CO_2, and CH_4. The relative quantity and composition of each product depend on operating conditions, such as reaction temperature, residence time, use of catalysts, as well as the feedstock type.

To obtain a high liquid product yield, fast pyrolysis is used. Fast pyrolysis requires temperatures of 500–650 °C and feed particles less than 3 mm in diameter (Mohan et al., 2006; Rogers and Brammer, 2012). The feed particles are resident in the reactor for 2–3 s, and the vapours produced are condensed into bio-oil. High bio-oil yields of up to 80 wt% can be achieved (Xiu and Shahbazi, 2012).

There are many types of reactor systems that perform fast pyrolysis including fluidised bed, circulating fluidised bed, auger, rotating cone and ablative, of which the first three have a strong technical grounding and are most attractive for commercial development (Butler et al., 2011). Auger pyrolysis has been selected as the reactor for this study because it has been suggested as an option for mobile facilities (Sorenson, 2010).

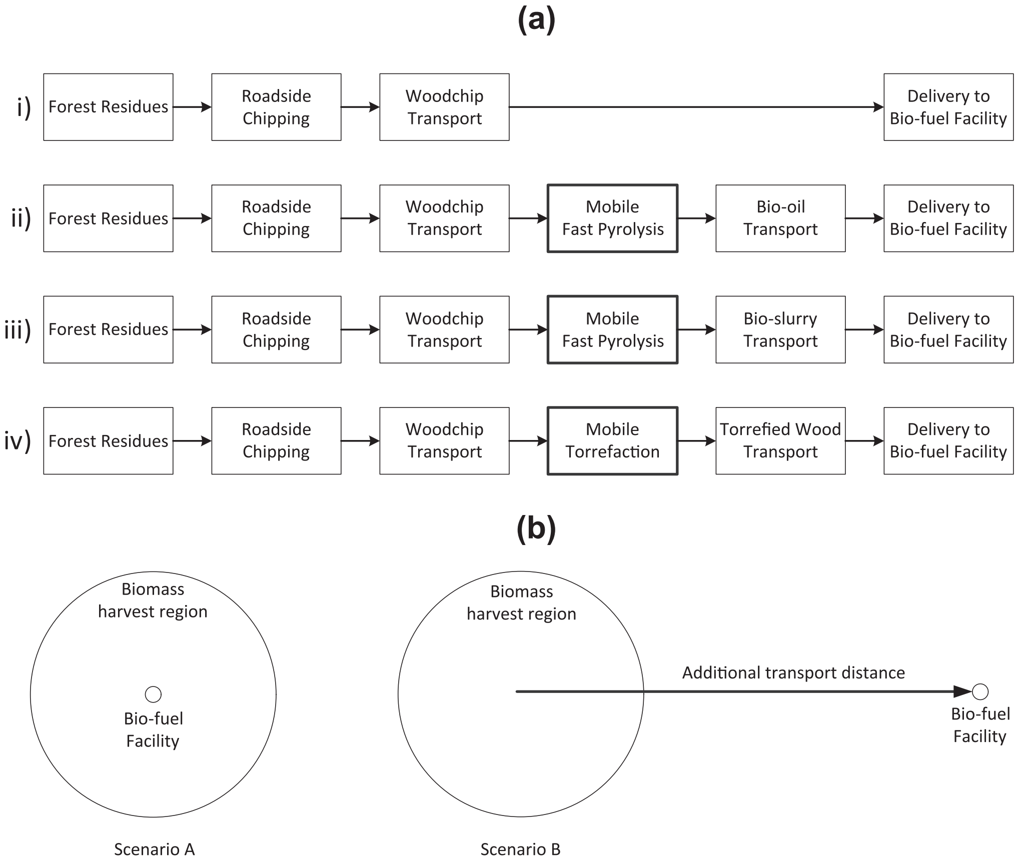


Fig. 1. (a) The four pathways to deliver a forest residue resource to a bio-fuel facility considered in this study. (b) Point-of-delivery scenarios.

Auger fast pyrolysis requires a feed composed of granules less than 3 mm in diameter with a moisture content of approximately 10%. The feed particles are passed into the reactor where they are indirectly heated to approximately 500 °C within 1 s, and the vapours produced are rapidly condensed into bio-oil. The feed system and reactor contain a screw conveyor to enable the process to run continuously. It is possible for the non-condensable syngas to be recycled within the reactor to provide process energy, and the solid char exits the reactor vessel for collection (Sorenson, 2010).

The typical yield of bio-oil tends to be lower for auger reactors compared to fluidised bed reactors as the vapours spend more time in the reactor vessel and secondary thermal break-down reactions occur (in contact with the solid char) reducing the quantity of vapours that condense into bio-oil (Bridgwater, 2012). The yields of auger pyrolysis used in this study are 57 wt% bio-oil, 26 wt% char and 15 wt% syngas (Fig. 2a). Ash is assumed to comprise 2 wt% of the products, and exits the reactor along with the solid char.

It is possible for the electrical and thermal energy requirements of a mobile fast pyrolysis facility to be supplied using fractions of the pyrolysis products. Thermal demands can be met using syngas, and electrical demands can be met by using bio-oil to power a generator. In cases of high initial moisture content, propane may be required for sufficient drying of biomass (Sorenson, 2010).

No mobile fast pyrolysis facilities have yet been commercialised, although there are a number of companies working on designs, such as Agri-Therm (Ontario, Canada) and Renewable Oil International (ROI) (Alabama, United States). ROI has manufactured a 5 oven-dry tonne per day (ODTPD) mobile facility and a 15 ODTPD fixed facility, and has plans to construct larger facilities (Preto, 2005). A 50 ODTPD mobile auger fast pyrolysis design by ROI was the focus of a recent study and is the subject of this analysis (Sorenson, 2010). The facility is permanently mounted on two 16 metre lowboy trailers, for ease of mobilisation. Technical and financial information are provided in Appendix A: Supplementary Information S.1.

1.1.1. Bio-oil

Fast pyrolysis liquid, known as bio-oil, has a lower heating value of 14–19 MJ kg^{-1} and a density of approximately 1200 kg m^{-3} (Oasmaa and Peacocke, 2001; Bridgwater, 2012). The properties of the bio-oil are strongly influenced by the feed used for the fast pyrolysis process. Bio-oil is often dark-brown in colour, and is a free-flowing heterogeneous mixture composed primarily of oxygenated hydrocarbons and water. The reactive oxygenated compounds such as acids, ethers, esters, aldehydes, ketones and alcohols cause undesirable properties including high viscosity, low pH, immiscibility with fossil fuels, thermal instability and a tendency to polymerize under exposure to air (Honkela et al., 2010; Bridgwater, 2012). Therefore, removing the oxygen content of bio-oil, in a process known as upgrading, is often required although it is possible to use raw bio-oil as fuel in a diesel or flex fuel generator (Sorenson, 2010).

Bio-oil is often stored in stainless steel tanks due to the corrosive nature of the liquid (Badger and Fransham, 2006). Secondary reactions within the bio-oil can occur over time in a process known as aging, which results in increased viscosity and in some cases, phase separation. The aging process is accelerated by the presence of fine char within the liquid, but can be reduced by the addition of alcohols such as ethanol or methanol (Bridgwater, 2012). Downstream options for utilisation of bio-oil include: electricity generation, bio-fuel production via upgrading, steam reformation to hydrogen, and production of chemicals.

1.1.2. Bio-slurry

Char produced from the fast pyrolysis reaction can be added to bio-oil up to 20 wt% to form a bio-slurry mixture that is flowable (Raffelt et al., 2006; Wu et al., 2010). Even low quality bio-oils, which are prone to phase separation and contain char and ash contaminates, are amenable to bio-slurry preparation. Adding bio-char to the bio-oil can allow up to 90% of the energy content of the pyrolysis products to be contained in the bio-slurry (Dahmen et al., 2012), making bio-slurry an attractive energy carrier for biomass. The density and energy content of bio-slurry varies depending on the char loading in the mixture, but is approximately 1300 kg m^{-3} and 30 MJ kg^{-1}, respectively, for a slurry containing 20 wt% char. Bio-slurry can be easily pumped into high pressurised gasifiers or other processing reactors (Raffelt et al., 2006).

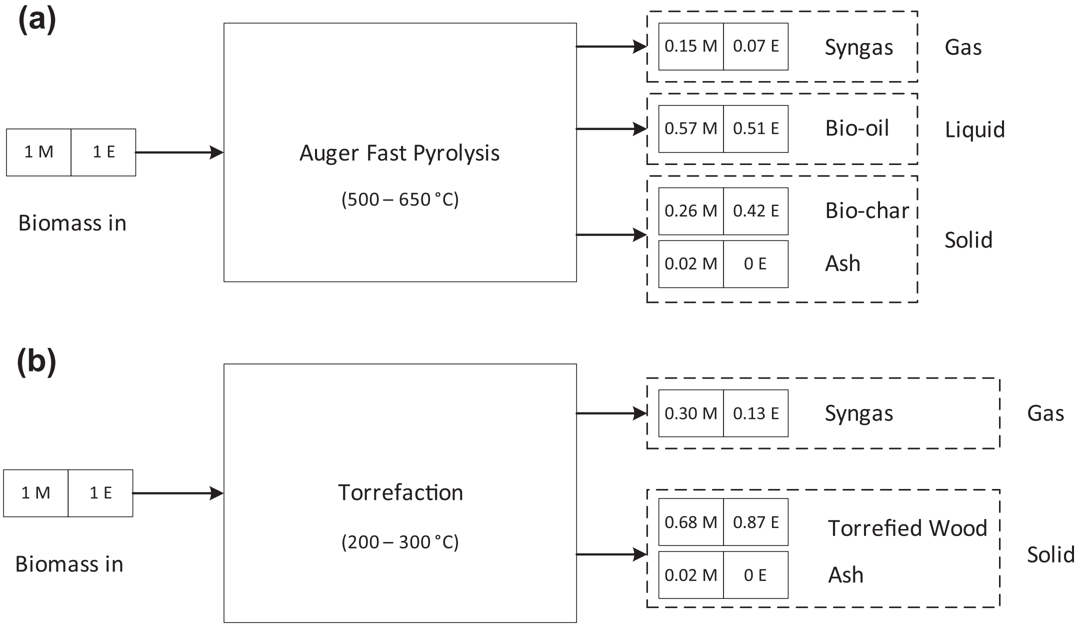


Fig. 2. Typical energy and mass balance for (a) auger fast pyrolysis and (b) torrefaction for a biomass input of mass M with energy content E (diagram modified from Bergman et al., 2005). Data taken from Sorenson (2010) and Bergman et al. (2005), and modified to yield suitable LHV values of products (syngas: 8 MJ kg^{-1}, bio-oil: 16.2 MJ kg^{-1}, bio-slurry: 18.8 MJ kg^{-1}, torrefied wood: 22.9 MJ kg^{-1}).

1.2. Torrefaction

Torrefaction is a mild pyrolysis process that requires temperatures of 200–300 °C to decompose the hemicellulose fraction of wood, creating a charcoal-like substance known as torrefied wood (Acharya et al., 2012). The process begins with initial drying of the biomass chips to a moisture content of approximately 10%. Torrefaction occurs when the temperature rises above 200 °C. The heating rate of the process remains relatively low (<50 °C per min) (Bergman et al., 2005). Traditionally residence times are up to 1 h, although at temperatures of 250–280 °C it has been shown that residence times as low as 8 min can provide torrefied wood with desirable fuel characteristics and grindability (Bergman et al., 2005).

Fig. 2b shows typical mass and energy balances of the torrefaction process. In general, 70% of the mass remains in the solid product, which contains up to 90% of the input biomass energy. The syngas produced by torrefaction can be used to meet thermal demands, depending on the reactor configuration. Propane may be required to assist with drying biomass and an external electricity supply may be required to power the process.

Commercial development of torrefaction has not yet been achieved, although auger torrefaction technology has proved a more popular reactor choice for development (Chew and Doshi, 2011). In North America, auger torrefaction technology has been designed and built at North Carolina State University. Using this technology, Agri-Tech Producers, LLP (South Carolina, United States) has recently been granted a patent and has plans to design mobile torrefaction facilities (Hopkins and Burnette, "Autothermal and mobile torrefaction devices," US Patent 8 304 590, April 3, 2009). Integro Earth Fuels, also based in North Carolina, has constructed a 100 ODTPD fixed site pilot facility in Gramling, South Carolina (Integro Earth Fuels, 2013). Renewable Fuel Technologies are a California-based company that has begun designs for a 25 ODTPD mobile torrefaction facility (Renewable Fuel Technologies, 2011).

No mobile torrefaction facilities are currently available, thus the technical parameters for torrefaction used in this study have been taken from the literature (Bergman et al., 2005; Uslu et al., 2008). A 50 ODTPD facility is assumed with the same initial cost as a mobile fast pyrolysis facility of an equivalent size, given that auger technology is used in both. Technical and financial information are provided in Appendix A: Supplementary Information S.1.

1.2.1. Torrefied wood

Torrefied wood has a higher energy density than raw biomass feedstock due to the removal of water (Uslu et al., 2008). The mass density of torrefied wood is lower than raw biomass feedstock, typically 180–300 kg m^{-3}, as the porosity is increased compared to that of the initial biomass. Torrefied wood is also more brittle than raw biomass, resulting in decreased mechanical strength, making it easier to grind or pulverise (Uslu et al., 2008). The chemical properties of torrefied wood are similar regardless of the source wood, and typical lower heating values range between 18 and 23 MJ kg^{-1} (Bergman et al., 2005). This uniformity of product is an advantage for downstream processes using torrefied wood as an input, such as combustion or gasification. Furthermore, torrefied wood is hydrophobic and is therefore more suitable for long term storage than fresh woodchips as fungal degradation is less likely (Arias et al., 2008).

2. Methods

This study investigates four alternative pathways for harvesting forest residues and delivering the biomass resource to a bio-fuel facility as either woodchip, bio-oil, bio-slurry, or torrefied wood (Fig. 1a). A model is constructed to analyse the technical and financial aspects of each pathway, and considers two point-of-delivery scenarios.

The model is constructed in Matlab, and is based upon the volume of forest residues that are available for harvest. The model performs mass and energy balances for fast pyrolysis and torrefaction processes, as shown in Fig. 2, and gross product yields are calculated. The quantity of products used to meet thermal and electrical demands of mobile facilities are calculated based on energy requirements for drying and electricity generation, both of which include process efficiencies (details are provided in Appendix A: Supplementary Information S.1). The mass and energy content of each product (net) delivered to a bio-fuel facility plant gate are then calculated. Furthermore, storage requirements at mobile facilities are calculated and transport distances necessary for forest residue harvest are determined. Financial calculations include the harvest and chipping of forest residues, the purchase, operating and labour requirements of mobile facilities, and transportation costs. The primary output of the model is a levelised cost of forest residue energy delivered to the bio-fuel facility ($ GJ^{-1}). The model is described in detail in Sections 2.1 to 2.4.

2.1. Point-of-delivery scenarios

Two point-of-delivery scenarios are considered in this study (Fig. 1b). In scenario A, the forest residue resource is delivered to a bio-fuel facility located at the centre of a biomass harvest region. This scenario models a situation where a bio-fuel facility is located within the forested region to purposefully use the local resource. In scenario B, feedstock is delivered to a bio-fuel facility outside of the harvest region, requiring greater transport distances. This scenario models a situation where an existing bio-fuel facility outside the forested region is the point of delivery.

2.2. Harvest and transport

Harvest and transport system models are important components of determining the cost of delivering a biomass resource to a bio-fuel facility. Models in the literature range from simple continuous models applicable to idealised situations (e.g. Overend, 1982), to those incorporating geographical information systems (GIS) that require details of landscape attributes and road networks (e.g. Sultana and Kumar, 2012). This study implements a discrete transport model (with no specific geographical setting) similar to those used in the literature (e.g. Wright and Brown, 2007; Sultana and Kumar, 2011), with modifications to account for the use of mobile facilities. The harvest and transport model is described in relation to woodchip delivery in Section 2.2.1, and pathways involving the use of mobile facilities in Section 2.2.2.

2.2.1. Woodchip delivery

The conventional method for using forest residues as a biomass feedstock requires transporting woodchips directly from the logging fields to a bio-fuel facility. In this process, residues are piled at the roadside where they are chipped directly into a chip van, which delivers the woodchips to their destination.

In the model, the extent of the harvest region is determined by both the volume of forest residues to be collected during the entire harvest operation lifetime and the spatial density of the biomass. The harvest region is assumed to be circular (Fig. 3a). The radius of the harvest region, R, is calculated as

$$R = \sqrt{HY/\rho\pi} \tag{1}$$

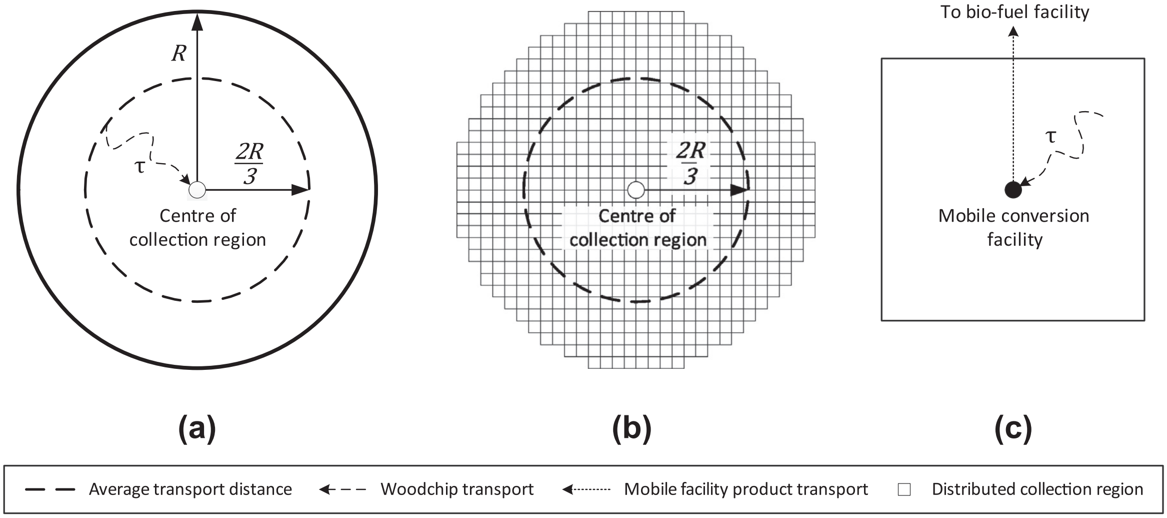

R
2R/3
τ
Centre of collection region
2R/3
Centre of collection region
To bio-fuel facility
τ
Mobile conversion facility
(a)
(b)
(c)
Average transport distance
Woodchip transport
Mobile facility product transport
Distributed collection region

Fig. 3. (a) Harvest and transport model for delivering a conventional woodchip feedstock. (b) Overview of harvest grid for harvest and transport model when implementing mobile facilities. (c) A distributed collection region with mobile facility at the centre.

(Wright and Brown, 2007) where H is the annual harvest measured in cubic metres, Y is the lifetime of the harvest operation in years, and ρ is the spatial density of available forest residues ($m^3\ km^{-2}$). For scenario A, the average annual distance, $\overline{D}$, to transport woodchips is calculated as

$$\overline{D} = \tau(2R/3) \tag{2}$$

where τ is a tortuosity factor to account for the winding of roads, usually ranging between 1.2 and 3 (Wright and Brown, 2007). In this analysis a value of 1.5 is used, which is consistent with other studies.

For scenario B, an additional distance, d, is included in the average transport distance (Eq. (2)) to account for the point of delivery being located at a distance from the biomass harvest region.

2.2.2. Mobile facility product delivery

Implementing distributed mobile facilities results in either bio-oil, bio-slurry or torrefied wood delivery to the bio-fuel facility, depending on the mobile facility chosen. Forest residues are chipped into chip vans and transported to the nearest mobile facility. Preparation of the woodchip feed is followed by either fast pyrolysis or torrefaction, and the associated product is then transported to the bio-fuel facility.

The transportation model used when implementing mobile facilities is shown in Fig. 3b and c. The size of the entire harvest region is defined using Eq. (1). Smaller square harvest regions are then assumed for distributed collection of forest residues. The number of distributed collection regions depends on the number of mobile facilities required to process the annual harvest, and also the number of times each facility is relocated over the lifetime of the harvest operation. The layout of the distributed collection regions is assumed such that no overlap occurs, thus representing a gridded version of the entire harvest region. The number of distributed collection regions, N_{grid}, is calculated as

$$N_{grid} = N_{mobile}(1 + n_r) \tag{3}$$

where N_{mobile} is the number of mobile facilities required to meet an annual harvest and n_r is the number of times each mobile facility is relocated over the lifetime of the harvest operation. The number of mobile facilities required varies depending on the annual harvest because the size of the mobile facilities is fixed. A larger annual harvest will demand more mobile facilities.

The grid details all the distributed collection regions that will be harvested over the operation lifetime. Each distributed collection region is only occupied once during the operation lifetime.

When harvesting forest residues within a distributed collection region, the average distance from any point in the square collection region to the mobile facility at the centre is calculated as

$$\overline{D}_{mobile} = \frac{1}{6}\tau\sqrt{H_{mobile}/\rho}\left(\sqrt{2} + \ln(1 + \sqrt{2})\right) \tag{4}$$

(Wright and Brown, 2008) where H_{mobile} is the amount of available forest residues within the distributed collection region to be collected whilst the mobile facility is at that location, defined as

$$H_{mobile} = \frac{\text{Total harvest over operation lifetime}}{\text{Number of mobile locations}} = \frac{HY}{N_{grid}} \tag{5}$$

The products of fast pyrolysis or torrefaction are transported using B-train trucks, assuming mobile facilities are located on sites with road networks adequate for larger vehicles. Once the forest residue resource in one grid location has been depleted, the mobile facility is relocated to an un-harvested grid location. For scenario A, the average distance to transport the products of the mobile facilities over the operation lifetime is found using Eq. (2). For scenario B, the additional transport distance is included in the average distance.

To maintain a continuous fast pyrolysis or torrefaction process a constant supply of woodchips is required. Therefore a storage pile of woodchips at the mobile facility site is necessary. Two days worth of storage for woodchips is assumed to allow for holidays or weekends when woodchip transport may not occur. For a 50 ODTPD facility, calculations show 2 days storage corresponds to 660 m^3 of woodchips. Bio-oil or bio-slurry product is stored in stainless steel tanks, holding 3 days worth of production from the fast pyrolysis process. Initial calculations prove this size of storage is similar to that of a liquid B-train tanker truck (Appendix A: Supplementary Information S.2) that would transport the products, and thus would provide effective delivery logistics. Storage requirements for torrefied wood on-site at the mobile facility are similar to that of woodchips. Two days worth of torrefied wood storage is assumed, which calculations show would allow receiving trucks of 200 m^3 capacity to completely fill from the storage area when arriving every 1.5 days.

2.3. Mobile facilities

The mobile facility processes are modelled using the system configurations shown in Fig. 2. Products yields and system requirements of mobile facilities are calculated in terms of energy.

For both fast pyrolysis and torrefaction, the produced syngas is used to dry woodchips at the mobile facility. The amount of energy required for drying is calculated based on the initial moisture content of biomass and the efficiency of the dryer (Appendix A: Supplementary Information S.3). If the energy content of produced syngas is not sufficient for drying, propane is imported to the mobile facility.

The electrical demands of mobile fast pyrolysis facilities are met using a portion of the produced bio-oil. The amount of bio-oil used for electricity generation is calculated based on the electrical requirements of the mobile facility and efficiency of electricity generation (Appendix A: Supplementary Information S.1). The electrical demand of a mobile torrefaction facility is assumed the same as a mobile fast pyrolysis facility, although it is likely to be lower as no grinding of woodchips is required. A diesel generator is used to power torrefaction facilities.

Once mobile facility process requirements have been addressed, the model calculates the net annual quantity of products to be delivered to the bio-fuel facility.

2.4. Costs

The model includes financial calculations to produce a levelised cost of delivering the forest residue resource to a bio-fuel plant gate (‘levelised delivered cost’). The levelised delivered cost is calculated on an energy basis to provide an equal comparison for each delivery pathway. The cost calculations in the model are detailed as follows.

The delivered cost of the forest residue resource to a bio-fuel facility plant gate, $c_{\text{delivered}}$, can be summarised as

$$c_{\text{delivered}} = c_{\text{biomass}} + c_{\text{mobile}} + c_{\text{transport}} \tag{6}$$

where c_{biomass} is the cost of purchasing, piling and chipping forest residues, c_{mobile} is the cost of purchasing and operating the mobile facilities (including feed preparation and storage requirements), and $c_{\text{transport}}$ is the cost of hauling woodchips and mobile facility products.

The value of c_{biomass} is the same whether mobile facilities are implemented or not. The cost of purchasing, piling and chipping forest residues are provided in Appendix A: Supplementary Information S.2. The purchase cost of forest residues is the fee for removal of fuels from the logging field (Sarkar et al., 2011). When woodchips are delivered directly to a bio-fuel facility, no mobile facilities are required and c_{mobile} is equal to zero. Implementing mobile facilities incurs costs associated with the purchase and operation of the facilities. Cost calculations relating to c_{mobile} are detailed in Appendix A: Supplementary Information S.4.

$c_{\text{transport}}$ includes the cost of transporting woodchips as well as the products of mobile facilities. For each commodity (i.e. woodchips, bio-oil, bio-slurry or torrefied wood), there is a fixed cost of transportation and a variable hauling cost. The fixed cost is associated with loading and unloading of trucks. The variable hauling cost depends on transport distances provided by the transport model detailed in Section 2.2, truck capacities, and the amount of each commodity to be transported.

The fixed costs of transportation are calculated using the loading and unloading costs provided in Appendix A: Supplementary Information S.2. The variable cost of transportation for commodity i, $c_{\text{variable},i}$, is calculated as

$$c_{\text{variable},i} = 2 \times k_i \times X_i \times M_i / M_{\text{truck},i} \tag{7}$$

(Sultana and Kumar, 2011) where k_i is the hauling cost for commodity i, X_i is the average distance the commodity is transported (either $\overline{D}$ or $\overline{D}_{\text{mobile}}$), M_i is the mass of commodity to be transported, and $M_{\text{truck},i}$ is the actual load carried by a truck, which depends on whether the trucks are limited by volume or by weight (Appendix A: Supplementary Information S.5). When mobile facilities are not implemented, the costs relating to product transport are equal to zero.

For each delivery pathway, all costs are collated, brought to present day value, and annuitized. The levelised delivered cost ($ GJ^{-1}) is calculated as

$$\text{Levelised delivered cost} = \frac{\text{CRF} \times \text{NPV}}{\text{Annual GJ of resource delivered}} \tag{8}$$

where CRF is the capital recovery factor, and NPV is the net present value of all costs (a discount factor of 10% is used).

2.5. Analysis performed

The model is used to determine the levelised delivered cost of a forest residue resource using each of the four delivery pathways.

Initially, a base analysis is performed for delivery to a bio-fuel facility within a forested region (scenario A) using base values outlined in Appendix A: Supplementary Information S.2. The annual harvest for the base analysis is 1.717 million m^3 (equivalent to delivering 2000 ODTPD woodchips), and is a standard base size of bio-fuel facilities used in the literature. The spatial density of forest residues assumed for the base analysis is 65 m^3 km^{-2}, which is consistent with temperate forest data used in other studies (e.g. Sarkar et al., 2011). The base analysis therefore considers a harvest region of 528,307 km^2 over a 20 year harvest operation. The forest residues are modelled with an initial moisture content of 50%, and an oven-dry wood bulk density and LHV of 500 kg m^{-3} and 18 MJ kg^{-1}, respectively.

Further analysis for scenario A is carried out to examine the impact of varying annual harvest requirements, spatial density of forest residues, transportation haul cost factors, moisture content of forest residues, and number of mobile facility relocations. These parameters are chosen for further analysis as they either prove important parameters in sensitivity analyses or are specifically related to the concept of using mobile facilities. The sensitivity analyses included both technical and financial parameters, but no variation of reactor configuration was analysed as product yields and characteristics (and mobile facility energy requirements) for alternative configurations have not been identified in the literature.

Finally, delivery to a bio-fuel facility located at a distance from the forested region (scenario B) is considered to investigate the impact of additional transport distance on feedstock delivery costs.

3. Results and discussion

3.1. Delivery to a bio-fuel facility located at the centre of a biomass harvest region (scenario A)

The results of the base analysis are detailed in Table 1. The levelised delivered cost of woodchips is 8.73 $ GJ^{-1} while the costs for bio-oil, bio-slurry and torrefied wood are 21.73 $ GJ^{-1}, 15.51 $ GJ^{-1} and 9.72 $ GJ^{-1}, respectively. The average transport distance is 273 km. Transport costs for woodchips account for over 80% of the final delivered costs. Implementing mobile facilities reduces the impact of transport costs to less than 40% of final delivered costs, yet for this size of annual harvest the costs of implementing mobile facilities outweigh the reduction in transport costs.

Table 1
Scenario A. Breakdown of levelised delivered cost for base harvest (1.717 million m^3 annual harvest).

Cost component (Eq. (6))	Woodchip		Bio-oil		Bio-slurry		Torrefaction	
	$/GJ	%[a]	$/GJ	%[a]	$/GJ	%[a]	$/GJ	%[a]
Biomass								
Forest residue purchase, piling & chipping	1.67	19.1	3.70	17.0	2.56	16.5	1.92	19.8
Mobile								
Feed preparation	–	–	6.80	31.3	4.70	30.3	0.72	7.4
Purchase & maintenance of mobile units	–	–	3.83	17.6	2.65	17.1	2.19	22.5
Labour	–	–	2.71	12.5	1.88	12.1	1.41	14.5
Relocation	–	–	0.01	0.0	0.00	0.0	0.00	0.0
Storage	–	–	0.00	0.0	0.00	0.0	0.00	0.0
Transport								
Woodchip delivery	7.07	80.9	1.67	7.7	1.15	7.4	0.87	8.9
Product delivery	–	–	3.01	13.9	2.57	16.6	2.61	26.9
Total	8.73	100.0	21.73	100.0	15.51	100.0	9.72	100.0

[a] Percentage of total levelised delivered cost.

Delivering woodchips ensures that all of the energy content of forest residues are delivered to the bio-fuel facility. When delivering bio-oil, bio-slurry or torrefied wood the total energy delivered to the bio-fuel facility is reduced due to the energy requirements of the mobile facilities, which use a fraction of the biomass energy content to meet thermal or electrical demands. Fast pyrolysis facilities use 12.4% of the produced bio-oil for electricity generation for the facility. Furthermore, the energy content of the char product of fast pyrolysis is not available for bio-fuel production when only bio-oil is delivered. Some of the char is transported when a bio-slurry is produced, although the configuration of the fast pyrolysis reactor in this study yields excess char that cannot be added to the bio-slurry due to a maximum char loading of 20%. Therefore, the total energy delivered by bio-oil, bio-slurry and torrefied wood is 45%, 65% and 87% of the initial forest residue energy content, respectively. The reduced quantity of energy delivered to the bio-fuel facility increases the levelised delivered cost of product.

Fig. 4a shows how the levelised delivered cost (Eq. (8)) for each pathway varies with annual harvest volume. Above a harvest of approximately 2.6 million m^3 per year it becomes more economical to implement mobile torrefaction facilities. The number of mobile facilities required increases with annual harvest volume (the size of the mobile facilities is fixed). However, the cost reduction provided on conventional woodchip transport direct to a bio-fuel facility means implementing mobile torrefaction facilities reduces the total levelised delivered cost of resource. The minimum delivered cost of product when using a mobile facility network (for both fast pyrolysis or torrefaction) occurs at an annual forest residue harvest of 167,000 m^3, which requires the use of only four mobile facilities. However, the average transport distance to the bio-fuel facility for this size of harvest is only 85 km, and conventional woodchip delivery is the lowest cost pathway.

Figs. 4b and c show the levelised delivered cost partitioned into three cost components (biomass, mobile, and transport as discussed in Section 2.4) for annual harvests of 0.429 and 4.292 million m^3 (500 and 5000 ODTPD woodchip equivalent). As the annual harvest increases, a larger portion of the levelised delivered cost of woodchips is due to transport. The portion of total levelised delivered cost attributed to transport is considerably smaller for pathways using mobile facilities.

Model results show that the spatial density of biomass affects the levelised cost of delivery for woodchips more than when implementing mobile facilities. Varying the spatial density between 20 and 100 $m^3\ km^{-2}$ results in a +60.2% and −14.5% change in cost for woodchip delivery, respectively. The delivered cost of products from mobile facilities varies by a maximum and minimum of +21.7% and −5.17% over the same spatial density range.

The conventional method of delivering woodchips is more sensitive to haul costs (Table 2). A 50% change in the woodchip haul cost factor impacts the levelised delivered cost of woodchips by 37.5%. The other pathways are less affected (between 0.95% and 1.19% change in levelised delivered cost) as woodchip transport distance is shorter when using mobile facilities. The haul cost factors for mobile facility products vary the final levelised delivered cost by a maximum of 12.2%. Mobile facility pathways are less influenced by haul cost factors because transport requirements are reduced.

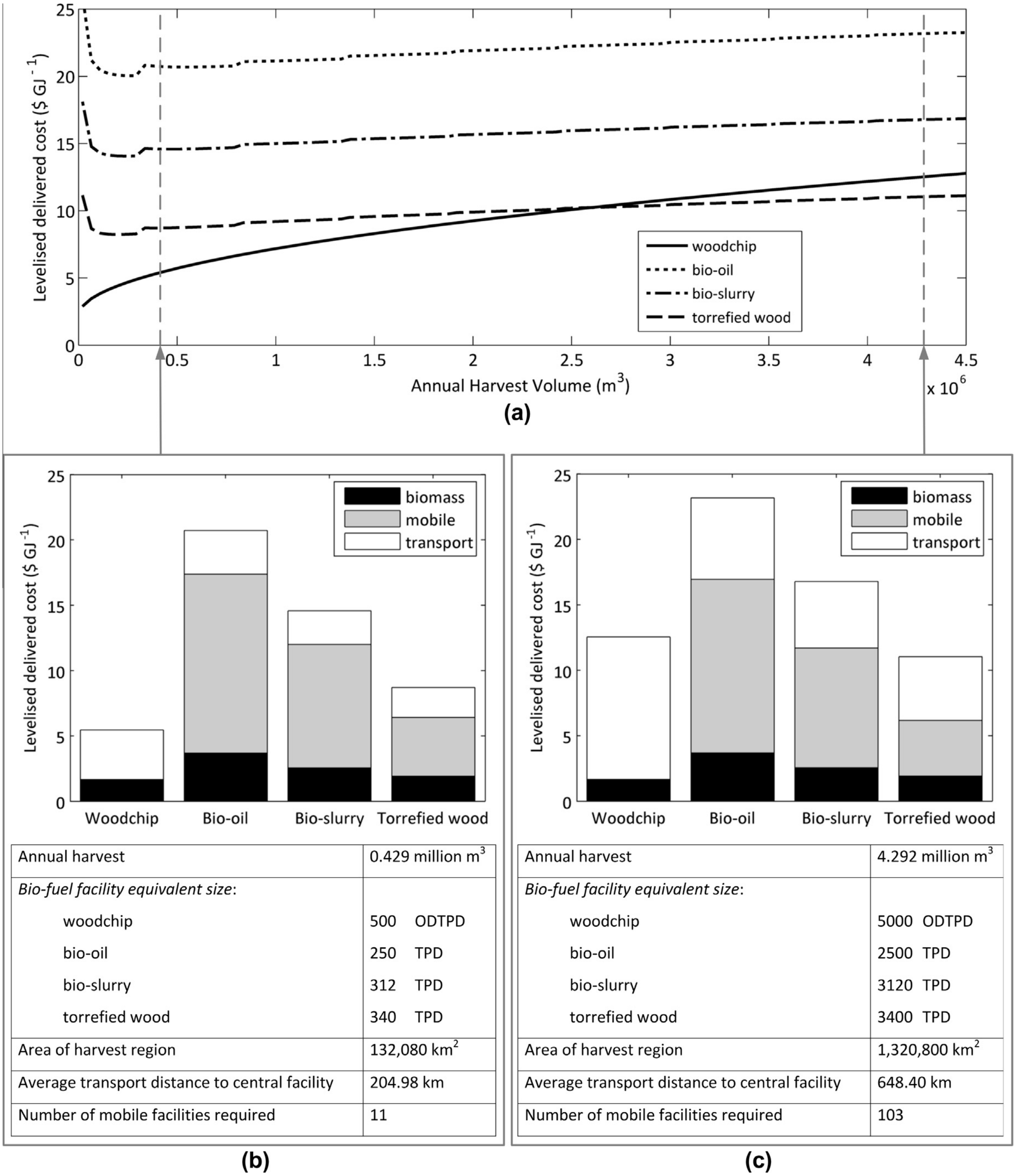
Moisture content of forest residues impacts the feed preparation energy requirements of mobile facilities. Each mobile fast pyrolysis facility requires 2937 L of propane per day when the initial moisture content is 50%. Each mobile torrefaction facility requires 689 L of propane per day. These quantities of propane account for approximately 30% (fast pyrolysis) or 7% (torrefaction) of the final delivered cost of product. For the configuration of the mobile facilities assumed in this study, the initial moisture content of the forest residues needs to be below 35% and 47% for no propane to be required to dry woodchips for fast pyrolysis and torrefaction, respectively. The effect of initial moisture content on levelised delivered cost is shown in Fig. 5a.

One advantage of using mobile facilities suggested in the literature is relocation of facilities. The levelised delivered cost, when using both types of mobile facility, is lowest when the facilities are relocated approximately 240 times (i.e. once per month for a 20 year operation). Relocating more frequently than this results in haul cost savings being offset by the cost of continuously relocating each mobile facility. The average woodchip transport distance to each mobile facility is 9.60, 2.57 and 1.96 km when mobile facilities are relocated 19 (annually), 240 (monthly) and 480 (every 2 weeks) times over the 20 year operation, respectively. The associated levelised delivered cost for a mobile torrefaction facility is 9.72 $\$\ GJ^{-1}$, 9.58 $\$\ GJ^{-1}$ and 9.60 $\$\ GJ^{-1}$ (Fig. 5b).

3.2. Delivery to a bio-fuel facility located at a distance from the centre of a biomass harvest region (scenario B)

In scenario B, the destination for delivery of woodchips, bio-oil, bio-slurry or torrefied wood is a bio-fuel facility located at an additional distance from the biomass harvest region.

Fig. 6a shows how the levelised delivered cost varies when the bio-fuel facility is located at an additional transport distance from the biomass harvest region, for an annual harvest of 1.717 million m^3 (equivalent to delivering 2000 ODTPD woodchips). Woodchip delivery is the lowest cost pathway for distances under approximately 50 km (base value haul costs). For greater distances,



(b)

Annual harvest	0.429 million m^3
Bio-fuel facility equivalent size:	
woodchip	500 ODTPD
bio-oil	250 TPD
bio-slurry	312 TPD
torrefied wood	340 TPD
Area of harvest region	132,080 km^2
Average transport distance to central facility	204.98 km
Number of mobile facilities required	11

(c)

Annual harvest	4.292 million m^3
Bio-fuel facility equivalent size:	
woodchip	5000 ODTPD
bio-oil	2500 TPD
bio-slurry	3120 TPD
torrefied wood	3400 TPD
Area of harvest region	1,320,800 km^2
Average transport distance to central facility	648.40 km
Number of mobile facilities required	103

Fig. 4. Scenario A. (a) Levelised delivered cost over a range of annual harvest volumes. (b) Cost components (Eq. (6)) for a bio-fuel facility of size 500 ODTPD (woodchip equivalent). (c) Cost components for a bio-fuel facility of size 5000 ODTPD (woodchip equivalent). The quantity of product delivered to the bio-fuel facility after conversion processes at mobile facilities is less than when delivering woodchips, and so the bio-fuel facility size required for each possible feed is also provided in 4b and 4c.

Table 2
Scenario A. The impact of woodchip (chip van) and mobile facility product (B-train) haul cost factors on final levelised delivered costs.

	Woodchip	Bio-oil	Bio-slurry	Torrefaction
	% Change in final levelised delivered cost			
50% increase base haul costs				
Woodchip hauling	+37.5	+1.15	+1.14	+0.95
Mobile facility product hauling	–	+6.12	+7.43	+12.2
50% decrease base haul cost				
Woodchip hauling	−37.5	−1.19	−1.14	−1.30
Mobile facility product hauling	–	−6.15	−7.43	−12.1

torrefied wood is the lowest cost pathway for delivering the forest residue resource. Bio-slurry is a less costly delivery pathway than woodchips at distances above 400 km, although the delivered cost of torrefied wood is still lower. If woodchip haul costs are as low as 0.85 $ km^{-1}, delivering woodchips is the lowest cost pathway for additional distances up to at least 500 km.

Fig. 6b shows the lowest cost delivery pathway for a range of annual harvests and additional transport distances. Bio-oil is always the most expensive pathway for delivering the forest residue resource, for the analysis range considered, followed by bio-slurry. Torrefied wood is a less costly pathway than both bio-oil and bio-slurry, and is also less costly than woodchips depending on the annual harvest volume and additional transport distance required. In Fig. 6b, implementing mobile torrefaction facilities is shown to be the lowest cost delivery pathway (for any annual harvest volume) when the point of delivery requires additional transport distances of more than 250 km. When there is no additional transport requirement, torrefied wood is the lowest cost delivery pathway when annual harvests are above 2.5 million m^3.

Of the four pathways considered to deliver a forest residue resource to a bio-fuel facility, woodchip delivery is the lowest cost option when annual harvests are small or transport distances are short. Implementing mobile facilities becomes economically attractive for larger harvests or when additional transport distances are required. Reductions in levelised delivered cost (Eq. (8)) for mobile facility pathways depend on (i) the purchase and operating costs of the mobile facilities (ii) the energy content of the products of mobile facilities (i.e. the conversion efficiencies of the mobile facilities), and (iii) the cost reductions of transportation when compared to conventional woodchip transport. Torrefied wood is the lowest cost pathway of delivering a forest residue resource when using mobile facilities, and is competitive with woodchip delivery at larger harvests and transport distances.

While the pathways have been compared on an energy delivered basis, each delivered product has distinct properties and characteristics. Pathways available for harvesting a forest residue resource may be limited as bio-fuel production opportunities vary depending on the feed type delivered to a bio-fuel facility. Woodchips, bio-oil, bio-slurry and torrefied wood are all suited for gasification (Bergman et al., 2005; Bridgwater, 2012), which produces syngas that can be used to synthesise bio-petrol or bio-diesel via

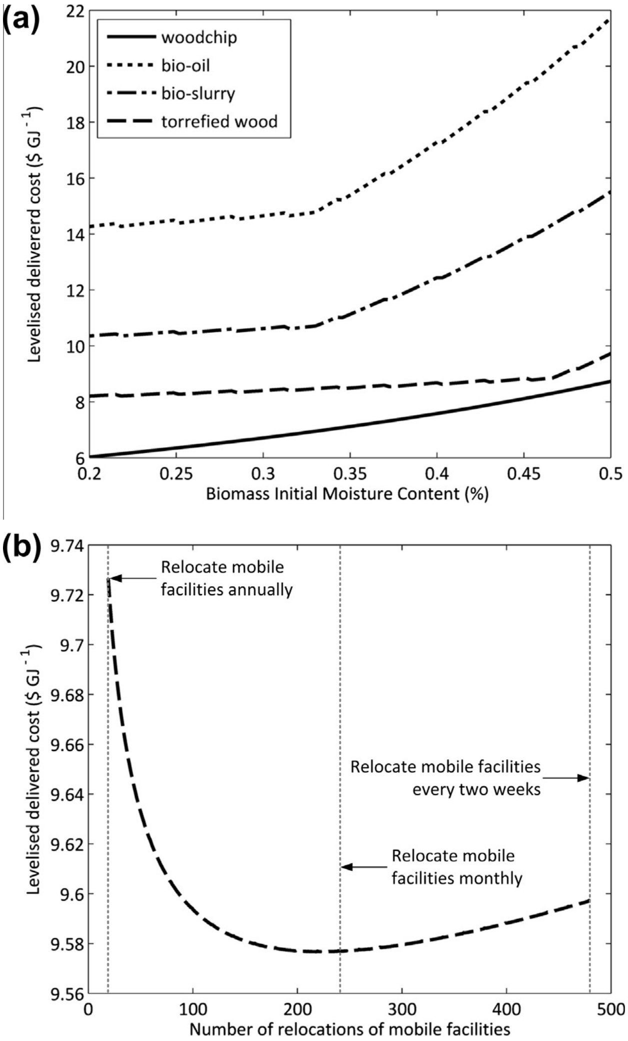


Fig. 5.. Scenario A. (a) Levelised delivered cost over a range of biomass initial moisture content (base harvest 1.717 million m^3). (b) Variation in levelised delivered cost of torrefied wood when relocating mobile torrefaction facilities (base harvest).

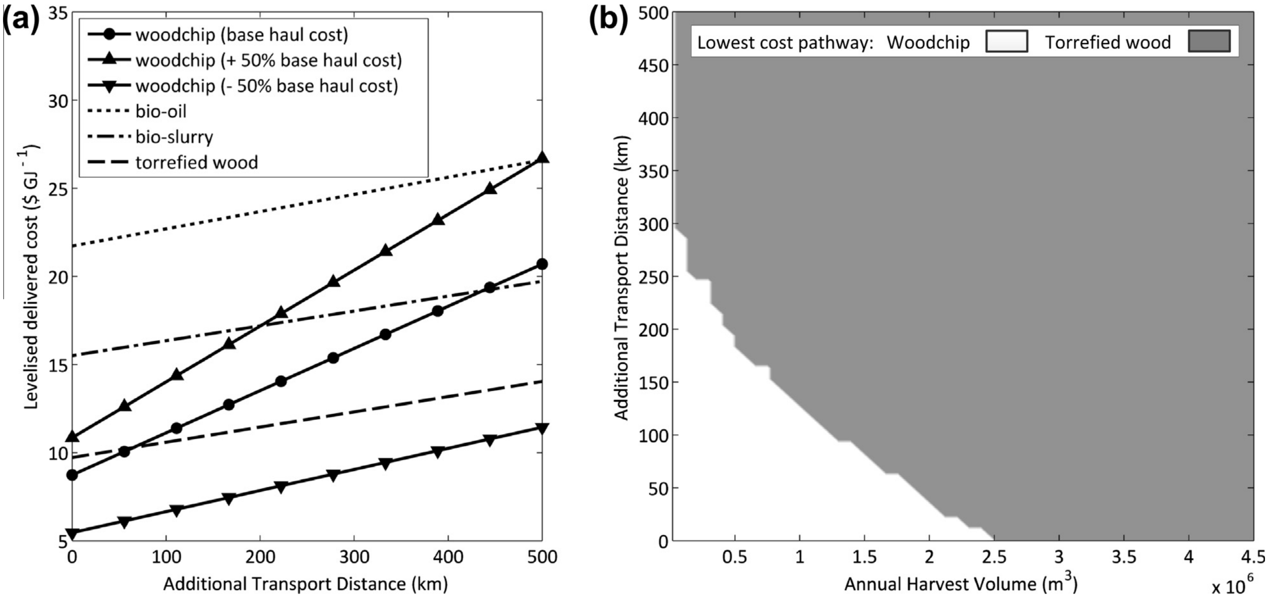


Fig. 6. Scenario B. (a) Levelised delivered cost when additional transport distances to a bio-fuel facility are required for an annual harvest volume of 1.717 million m^3, (2000 ODTPD woodchip equivalent). (b) Visualisation of lowest cost delivery option for a range of harvest volumes and additional transport distances.

Fischer–Tropsch reactions or hydrogen via the water gas shift. (The delivered cost of woodchips in this analysis relates to green woodchips and, whereas the products of mobile facilities can be used directly as a feedstock upon delivery, drying of woodchips will likely be required before they can be used for gasification). Alternatively, bio-oil may be upgraded to produce bio-petrol or bio-diesel, or can undergo steam reformation to produce hydrogen. Therefore, the choice of mobile facility used in a distributed collection network also depends on the type of bio-fuel production facility. Any economic advantage of delivering biomass resources using a mobile facility network would need to be considered alongside acceptable feed types for a bio-fuel production facility, as the final cost of biofuel will also depend on the economics of the bio-fuel facility.

Configuration of mobile facilities for optimal product yields could be beneficial for decreasing the delivered cost of mobile facility products. Ensuring sufficient syngas is produced to meet drying and thermal requirements of the facilities would remove the costs of purchasing propane. However, increasing syngas production would likely decrease the yield of other products to be delivered to the bio-fuel facility.

The model presented in this study provides a general analysis of using mobile facilities to harvest forest residues. However, biomass is a spatially and temporally dependent resource, and further considerations are necessary when examining particular geographic regions. Transport distances, hauling costs and sites available for mobile facilities require knowledge of the availability and location of the forest residue resource, as well as the local road network. These considerations are also useful when investigating the impact and cost savings possible from the relocation of mobile facilities.

Finally, utilisation of any biomass resource requires a sustainable approach. Continuous examination of bio-energy systems should be performed to ensure that no adverse affects arise from forest residue removal at logging sites. Particular concerns and issues that are areas of current research include forest residue removal impact on soil productivity and biodiversity e.g. (Lamers et al., 2013). Re-distributing the solid products of mobile facilities (e.g. bio-char) back into soils at forestry sites has been proposed as an option for soil remediation after removal of forest residues, although continued research is suggested.

4. Conclusion

The cost of delivering a forest residue resource to a bio-fuel facility using mobile facilities can be lower than using conventional woodchip delivery methods. Cost savings occur for large annual harvests of forest residues and when large transport distances are required. Torrefied wood is the lowest cost pathway of delivering a forest residue resource when using mobile facilities.

Important parameters that influence levelised delivered costs are transport distances (biomass spatial density), haul cost factors, and initial moisture content of forest residues. Relocating mobile facilities can be optimised for lowest cost delivery as transport distances of raw biomass are reduced.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.biortech.2013.10.018.

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